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NAMRL-1387

**EFFECTS OF METHAMPHETAMINE  
AND FATIGUE ON LONG- AND  
SHORT-TERM MEMORY**

**R.R. Stanny, A.H. McCardie,  
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**Naval Aerospace Medical Research Laboratory  
Naval Air Station  
Pensacola, Florida 32508-5700**

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**NAVAL AEROSPACE MEDICAL RESEARCH LABORATORY  
NAVAL AIR STATION, PENSACOLA, FL 32508-1046**

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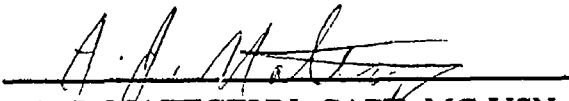
**94-06922**



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Reviewed and approved 4 Nov 93

  
A. J. MATECZUN, CAPT, MC USN  
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This research was sponsored by the Naval Medical Research and Development Command under work unit 63706N M0096.002-7010.

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## ABSTRACT

We examined the effects of a 10 mg/70 kg oral dose of *d*-methamphetamine HCl on fatigue-related deficits of long- and short-term memory. We used a recognition memory-search task with two memory loads. In one experimental condition, stimuli were committed to long-term memory and performance was rendered automatic by extended practice with consistently mapped stimuli and responses. In a second condition, the task was organized so that performance depended on short-term memory, despite equally extended practice. After 7680 training trials, 13 subjects performed the task at 90-min intervals in a 13.5-h sustained-performance session that began at 1930 hours and ended at 0900. At 0116 hours, seven subjects were administered capsules containing 10 mg/70-kg body weight *d*-methamphetamine HCl, double-blind. The remaining subjects were administered a placebo. Memory-trace strengths and decision speeds decreased during the night in long- and short-term conditions alike. Although long- and short-term strengths both decreased, the decline in long-term strengths was smaller, suggesting that extensive consistent training had produced memories comparatively resistant to fatigue. The methamphetamine treatment reversed the declines in strength and decision speed within approximately 2 h of administration. Furthermore, methamphetamine reversed an initial increase in lapse probabilities and largely suppressed lapses thereafter. That methamphetamine simultaneously increased memory strengths and decision speeds indicates that the stimulant did *not* merely produce criterion shifts that led subjects to respond impulsively (i.e., more rapidly but less accurately). A confirmatory analysis of trends in fast guesses (implausibly short decision times) revealed no evidence to suggest that the methamphetamine treatment produced an increase in impulsive responding. The overall pattern of the results suggests that methamphetamine substantially reduced impairments of both long- and short-term memory caused by extended performance during sleep loss.

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## ACKNOWLEDGEMENTS

In particular, we thank our volunteer subjects from the Marine Air Training Support Group and the Naval Schools Command for participating in the study. HMCS(SW) Robert Ford, HM1(AW) Teneal Flowers, ET1(SW) Barry Jacobsen, HM1 José García, HM2 Vincent Foti, HM2 Michael Stiney, HM2 Wanda Chapman, HM2 Derrick Epps, HM3 Diane Hernandez, Jon Sheely, and Jack Saxton provided considerable technical, medical, and logistical support. We thank LCDR Scott Shappell and Charles DeJohn for helpful discussions. Sam J. LaCour wrote most of the computer programs. LT Douglas Wiegmann, LT David McKay, John O. de Lorge, and Kathleen Mayer provided valuable critiques of earlier versions of the manuscript.

## INTRODUCTION

This study examined the effects of a 10 mg/70 kg oral dose of *d*-methamphetamine HCl on memory deficits that occur when performance must be sustained for long periods of time. The term 'sustained performance,' as used here, will refer to mental work performed continuously for a long period despite fatigue, sleep loss, and circadian phenomena. This definition is intended to parallel that of 'sustained operation' which is defined as continuous combat with no opportunity to sleep (U.S. Army, 1983). The performance scenario we examined required subjects to work continuously through a night of sleep deprivation following an ordinary day's activities. Similar patterns of continuous work and sleep deprivation occur in sustained air operations during rapid deployments, extended patrol missions, and long-range attack missions; civilian examples include lengthy medical-emergency procedures, long search-and-rescue operations, disaster-relief missions, accident evacuations, and forest-fire fights (Krueger, 1989).

The effects of maintaining performance over long periods include irritability, forgetfulness, mental lapses, a growing aversion to further effort and, sometimes, hallucinations (Bartlett, 1943; Bills, 1931; Hockey, 1986; Patrick & Gilbert, 1896; Warren & Clark, 1937; Williams, Lubin, & Goodnow, 1959). These effects undoubtedly derive from interactions among fatigue, sleep-loss, and circadian phenomena (Hockey, 1986; Krueger, 1989). An historically important hypothesis is that the sleep-loss effects are expressed as periodic lapses or microsleeps that intrude on otherwise normal performance (Broadbent, 1963; Williams et al., 1959). Broadbent (1963) suggested that performance during sleep loss more nearly resembles an engine periodically misfiring than a wind-up toy running down.

Early studies of sleep deprivation clearly documented its deleterious influence on memory (Edwards, 1941; Patrick & Gilbert, 1896; Weiskotten & Ferguson, 1930). Williams, et al. (1959) observed that sleep loss impaired short-term recall but had little effect on the long-term recall of items memorized before sleep had been lost. These observations led Williams et al. (1959) to suggest that the memory deficits caused by sleep loss may not be caused by failures of long-term-storage or retrieval processes. Instead, Williams et al. suggested that the effects of sleep deprivation on memory might be caused by failures of sensory registration or trace formation. In particular, they suggested that lapses occurring during sleep loss might degrade stimulus registration, thereby impairing subsequent recall.

Williams, Gieseeking and Lubin (1966) tested the hypothesis that the effects of sleep deprivation on memory are due to lapse-related failures of sensory registration by having sleep-deprived subjects write down to-be-remembered items as they were presented. This ensured that lapses did not (totally) block the sensory registration of the items to be remembered. Despite the fact that subjects had written down each word, and were corrected by the experimenters when they made a mistake, short-term recall was impaired nearly as much as it had been in the study of Williams et al. (1959), in which no attempt had been made to control for the effects of lapses. This result suggested that the memory deficits caused by sleep loss might *not* be largely attributable to failures of sensory registration.

To control for effects of sleep loss on rehearsal processes, Williams et al. (1966) performed another experiment in which the stimuli were pictures of faces, which they assumed would be much less easily rehearsed than words. Subjects examined a set of pictures, were deprived of sleep for 34 h, and then were tested for their ability to recognize the pictures. The accuracy with which sleep-deprived subjects recognized the pictures was only slightly (and nonsignificantly) worse than that of control subjects who had not been sleep deprived. This result suggested that memories created before sleep is lost may be relatively resistant to sleep-deprivation effects and confirmed the observation of Williams et al. (1959) that memories of words acquired before sleep loss are relatively well stored and retrieved. In contrast, pictures first shown to subjects during the course of sleep deprivation were poorly recognized when shown again 24 h later after a night of recovery sleep. Given the validity of the assumption that the pictures used by Williams et al. (1966) prevented rehearsal (which might be questionable), this result suggests that sleep loss impairs the creation of new memories in some way other than

by impairing rehearsal. Having thus ruled out registration, rehearsal, storage, and retrieval processes, Williams et al. (1966) concluded that sleep loss must impair the formation of memory traces.

More recent studies of the effects of sleep deprivation on memory have yielded results suggesting that these effects might, in fact, be accommodated by a sensory-registration hypothesis. At least two studies of recognition have yielded evidence consistent with the idea that sleep loss reduces the initial (acquisition) strengths of memories without affecting their susceptibility to interference and (thus) forgetting (Elkin & Murray, 1974; Polzella, 1975). These studies were motivated by trace-strength theory (Wickelgren & Norman, 1966), according to which the strength of a memory trace declines exponentially as a function of the interference produced by subsequent stimuli. That is:

$$d' = \alpha\phi^i + \lambda, \quad (1)$$

where  $d'$  is the strength of the trace at testing,  $\alpha$  is the strength of the trace at acquisition,  $\phi$  is the reduction in strength caused by an interfering stimulus,  $i$  is the number of interfering stimuli between learning and testing, and  $\lambda$  is long-term strength (the asymptotic value approached by  $d'$  as the number of interfering stimuli becomes large).

Polzella (1975) measured the effects of sleep loss on the parameters of equation 1 in a probed recognition task. He found that sleep loss reduced the acquisition and long-term strength parameters but did not influence the interference parameter. Elkin and Murray (1974) had previously reported similar results for the acquisition and interference parameters but did not report estimates of long-term strength. These results suggest that sleep loss reduces the initial strengths of traces but does not affect rates of forgetting. Polzella (1975) argued that such effects would be expected if lapses were to impair the encoding of stimuli into short-term memory. Impaired encoding would account for reduced acquisition strengths. One might suspect that impaired encoding could also reduce long-term strength. Polzella noted that the method of Williams et al. (1966), who attempted to control for the effects of lapses by having subjects write down stimuli as they heard them, would not be expected to control for the effects of lapses during the interval between memorization and recall. Lapses during this interval would (at a minimum) reduce the rehearsal time available to subjects. Because recall varies directly with amount of rehearsal (Rundus & Atkinson, 1970), other factors held constant, lapses that prevent rehearsal would be expected to impair recall.

## EFFECTS OF STIMULANTS ON HUMAN PERFORMANCE AND MEMORY

A comprehensive review of the amphetamines' effects on performance can be found in a companion paper (Stanny, McCardie, & Neri, 1993). The review that follows discusses effects of methamphetamine on human performance and effects of amphetamine-like stimulants in general on memory. Recent studies of the effects of methamphetamine on performance have yielded equivocal results. Mohs, Tinklenberg, Roth, and Kopell (1978) examined the effects of a 10-mg, oral dose of methamphetamine on visual-search, divided-attention, and time-production tasks in rested subjects. Methamphetamine reduced reaction time (RT) in the visual-search task but did not significantly affect performance in the divided-attention and time-production tasks. Mohs et al. (1978) did not report error rates, so their results do not indicate whether methamphetamine's effect on RT was due to improved visual-scanning performance or was simply the result of a response-criterion shift.

Mewaldt and Ghoneim (1979) examined the effects of 0.2 and 0.3 mg/kg intramuscular injections of methamphetamine on delayed free recall and recognition in rested subjects. In delayed free recall, the methamphetamine treatment yielded small increases in the probabilities with which subjects correctly recalled words from study lists. However, the increases in correct-recall probabilities following methamphetamine injection were accompanied by large increases in the probabilities with which subjects recalled words that had not been in the study lists. Mewaldt and Ghoneim suggested that, rather than improving recall, the drug may

have induced subjects to adopt less conservative retrieval criteria, thus causing them to generate more answers, most of which were incorrect.

When Kennedy, Odenheimer, Baltzley, Dunlap, and Wood (1990) examined the effects of *d*-amphetamine on memory search, they found that *d*-amphetamine increased accuracy. Unfortunately, these investigators reported neither RT nor set-size effects. Shappell, Neri, and DeJohn (1992) examined the effects of an oral dose of 10 mg/70 kg methamphetamine on moderately fatigued subjects in a sustained-performance experiment. The methamphetamine treatment yielded trends suggesting that the drug may have reduced fatigue effects on performance in a spatial short-term memory task (successive pattern comparison) and in a spatial station task. Fatigue effects on choice RT, mental arithmetic, grammatical reasoning, and time estimation were unaffected by the methamphetamine treatment.

Amphetamines have been reported to improve memory in a number of studies involving nonhuman subjects (e.g., M'Harzi, Willig, Costa, & Delacour, 1988; Packard & White, 1989; Quartermain & Judge, 1983; Quartermain & Jung, 1989; Sara & Deweer, 1982; Strupp, Bunsey, Levitsky, & Kesler, 1991). In contrast, Ljungberg and Enquist (1987) have reported observing amphetamine-induced disruption of learned action sequences in rats that, nevertheless, were able to perform the separate behaviors comprising the sequences. These authors concluded that, contrary to studies using simple tasks in which motor output is directly related to measures of performance, amphetamines do not increase performance in an adaptive way in more complex tasks.

## THEORY OF MEMORY SEARCH

Sternberg (1966, 1969) first documented the effects of memory load on the time-course of visual recognition. Sternberg observed that the time needed to make a correct recognition increases linearly with memory load (the number of items memorized, "memory-set size"). In Sternberg's (1966, 1969) data, the slopes of functions relating correct-response RTs to memory-set sizes averaged about 40 ms/item. The linearity of the RT functions led Sternberg to suppose that a recognition decision is made by comparing the sensory representation of a recognition probe to the internal representation of each memory-set item in sequence, and that the time required to make each comparison is independent of set size. Because the slopes of the RT-versus-set-size functions were nearly equal for correct "Yes" and "No" decisions, Sternberg concluded that the process of comparing a probe to a memory set is exhaustive. That is, a recognition probe is always compared to each item in the active memory set; the comparison process does not terminate if a match is found. The possibility that the comparison process terminates when a match is found seemed unlikely: A sequential process terminating on a match should yield different slopes for the RT functions of correct positive and correct negative decisions. This is because, for memory sets of  $m$  items, an average of only  $m/2$  comparisons should be needed to correctly determine that a probe matches one of the items in the set. In contrast,  $m$  comparisons should be needed to correctly determine that a probe matches none of the  $m$  items. Hence, if comparisons terminate on a match, and the time per comparison is constant, the ratio of slopes for correct positive and correct negative decisions should average 1:2. Sternberg's (1966, 1969) empirical results indicated that this ratio was more nearly 1:1, a value consistent with the idea that a recognition probe is always compared to every item in the active memory set.

Many investigators have examined the effect of set size on recognition RT since Sternberg's initial reports. Not all have corroborated the model Sternberg proposed. Of note, when stimuli are randomly assigned on each trial to memory or distractor sets (varied mapping, VM), performance usually follows a pattern similar to that reported by Sternberg (1966, 1969). Under these conditions, performance changes relatively little with practice (Kristofferson, 1972a). However, when each stimulus is consistently associated with a single response (consistent mapping, CM), the effect of set size on RT gradually decreases and, after sufficient practice, may nearly disappear (Kristofferson, 1972b; Schneider & Shiffrin, 1977; Shiffrin and Schneider, 1977).



Schneider and Shiffrin (1977) and Shiffrin and Schneider (1977) argued that these differences between VM and CM conditions reflect the operation of fundamentally different information-processing modes: attentionally controlled and automatic. Attentionally controlled processing depends on short-term working memory. Controlled processing occurs when stimuli are not always associated with the same responses (i.e., in VM conditions). Controlled performance tends to be slow, effortful, serial, under voluntary control, and sensitive to processing load (Schneider, 1989; Schneider & Detweiler, 1988; Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). Examples of attentionally controlled tasks include dialing new telephone numbers and activating weapon systems with inconsistent arming sequences (Schneider, 1989). Controlled processing is generally thought to typify novice performance. However, it may persist in the performance of variably mapped tasks despite months of training (Schneider & Shiffrin, 1977).

Automatic processing, in contrast, depends on well-learned, long-term memories. It is typically established by extensive practice with consistently mapped stimuli and responses (Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977).<sup>1</sup> Automatized performance tends to be fast, effortless, reliable (accurate), parallel, relatively unaffected by processing load, and difficult to inhibit once initiated (Schneider, 1989; Schneider & Detweiler, 1988; Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). Examples of automatized tasks include dialing well-learned telephone numbers, touch typing, sight-reading music, aircraft engine shutdown sequences, and ejection procedures. The achievement of a degree of automaticity is arguably a defining characteristic of the skilled performance of a task (Schneider, 1989; Schneider & Detweiler, 1988).<sup>2</sup>

The reliability of automatic processing has been held to make it more resistant than controlled processing to effects of stress. Evidence consistent with this idea includes reports that training to automaticity can render performance resistant to effects of heat stress (Hancock, 1986), vigilance demands (Fisk & Scerbo, 1987; Fisk & Schneider, 1981), and alcohol ingestion (Fisk & Schneider, 1982). Exceptions to these results, however, have been reported by Maylor and Rabbitt (1988), who found that automaticity did not reduce the negative effects of alcohol intoxication on visual search and word-categorization tasks.

## EFFECTS OF STIMULANTS ON MEMORY-SEARCH PERFORMANCE

Methylphenidate-related improvements in memory search performance have been reported in several studies. Brumaghim, Klorman, Strauss, Lewine & Goldstein (1987) reported two studies of the effects of 0.3 mg/kg methylphenidate on the memory-search performance of rested subjects. In both studies, methylphenidate shortened RTs and reduced errors. Of note, methylphenidate shortened RTs by approximately the same amount for each memory-set size examined, suggesting that the stimulant did not shorten RT by influencing search and decision processes (or, at least, that methylphenidate did not influence any search and decision processes that have durations that increase with memory-set size). Similar reductions in RT independent of memory-set size have been obtained in several other memory-search experiments (Coons, Klorman, & Borgstedt, 1987; Fitzpatrick, Klorman, Brumaghim, & Keefover, 1988; Pelloquin & Klorman, 1986). In two separate experiments, Fowler, Hamilton, and Porlier (1986, 1987) obtained no effect of *d*-amphetamine alone, but did

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<sup>1</sup>Some types of automatic information processing may be innate (Hasher & Zacks, 1979). The present discussion is concerned only with processes that become automatized with consistent training.

<sup>2</sup>Several reports suggest, plausibly, that automaticity is a matter of degree, not an all-or-none phenomenon (Cohen, Dunbar, & McClelland, 1990; Kohnen & Henik, 1981; MacLeod & Dunbar, 1988). We do not think the correctness of this idea bears strongly on the interpretation of our results. For simplicity, we will use the terms "controlled" and "automatic" in the sections that follow to refer to processes that might be as well (or better) described as "relatively controlled" and "relatively automatic."

find that amphetamine compensated for increased RTs caused by nitrous oxide inhalation by reducing RTs a constant amount independent of set size.

In the first study reported by Brumaghim et al., the methylphenidate treatment yielded no reduction in the latencies of concurrently recorded P300 event-related brain potentials. Some evidence suggests that changes in P300 latencies are associated with changes in the durations of stimulus-evaluation processes, but are relatively independent of changes in the durations of response-related processes (Magliero, Bashore, Coles, & Donchin, 1984; McCarthy & Donchin, 1981). Thus, Brumaghim et al. suggested that the absence of an effect on P300 latency in the presence of a reduction in RT was consistent with the idea that (in study 1) methylphenidate shortened RTs by influencing response-related processes. Similar reductions in memory-search RTs without corresponding reductions in P300 latencies have been observed by Coons et al. (1987), Fitzpatrick et al. (1988), and Peloquin and Klorman (1986).

In study 2 of Brumaghim et al. (1987), however, both RT and P300 latency were shortened by methylphenidate. In contrast to the results of study 1, these results suggested that methylphenidate may have shortened RTs by influencing stimulus-evaluation (or earlier) processes. Although studies 1 and 2 differed in several procedural details, Brumaghim et al. concluded that none of these provided a convincing explanation of the difference in results. Similar reductions in P300 latencies following *d*-amphetamine administration have been observed by Halliday, Naylor, Callaway, Yano, and Walton (1987).

## EFFECTS OF STIMULANTS ON RESPONSE BIASES

An unanswered question regarding the effects of amphetamines on performance concerns whether the increased response speeds frequently observed following the administration of stimulants are, in fact, attributable to increased information-processing efficiency. Hockey (1986), for example, has noted that the increased decision speeds attributed to stimulants might actually reflect changes in response criteria (shifts toward overly confident, impulsive responding). If this is true, some evidence ordinarily cited as indicating that amphetamines improve performance may, in fact, indicate the opposite. The answer to this question is of considerable practical interest because bias shifts not offset by improvements in efficiency may seriously impair performance.

The degree to which amphetamines at standard doses affect response criteria is unclear partly because experimental protocols used to study amphetamine effects have frequently confounded changes in performance efficiency with effects of altered response criteria. In particular, many investigators have inferred changes in efficiency from changes in RT without ruling out speed-accuracy trading as an explanation, despite the fact that an impulsive criterion shift no change in efficiency will yield the same effect on RT as an increase in efficiency with no change in criterion (Hockey, 1986). The study described here addressed this issue by employing a comparatively large number of observations per subject. This strategy allowed us to obtain accuracy and RT measures reliable enough to yield clear evidence of any speed-accuracy trading that may have occurred.

## METHODS

### SUBJECTS

The volunteer subjects were 13, male, Navy and Marine aviation candidates stationed at Pensacola Naval Air Station. Their ages ranged from 22 to 27 years ( $M = 24.00$ ,  $SD = 2.00$ ); their heights were 173-191 cm ( $M = 180.14$ ,  $SD = 5.64$ ); and their weights were 64-89 kg ( $M = 77.22$ ,  $SD = 8.48$ ). All

subjects had normal or corrected-to-normal vision. All subjects were medically screened before and after participating.

## EXPERIMENTAL TASK

We used a fixed-set memory-search procedure. Subjects were allowed 10 s to memorize a set of letter stimuli (the "memory set"). Memory sets contained either one or four letters. The memory-set letters were presented simultaneously on the computer screen. Beginning 2.0 s after the memory set had been turned off, 30 probe letters were presented, one at a time, for 1.5 s each at 2.0-s interonset intervals. Subjects were asked to respond "Target present" or "Target absent" to each probe letter to indicate whether it had been a member of the preceding memory set. Fifteen randomly selected probes that followed each memory set were elements of the memory set (targets); the remaining 15 probes were not elements of the memory set (nontargets). Subjects entered their responses by pressing the F and J keys of the computer keyboard with the first fingers of their left and right hands, respectively. The assignment of dominant and nondominant hands to "Target present" and "Target absent" responses was counterbalanced across subjects.

Each block of memory-search trials contained 32 memory sets. Each memory set was followed by 30 probe stimuli. At random, half of the memory sets in each block contained one letter; the remainder contained four letters. The one-letter memory sets and their associated probes comprised the low-memory-load, set size 1 (SS1) condition. The four-letter memory sets and their probes comprised the high-memory-load, set size 4 (SS4) condition. A random 50% of the memory sets in each block contained letters that were used only as target probes and never as nontargets. Furthermore, nontargets used with these memory sets were never used as targets. These memory sets and their probes comprised the consistent mapping (CM) condition. The remaining memory sets and their probes consisted of stimuli that randomly exchanged roles as targets and nontargets. These stimuli comprised the varied mapping (VM) condition. The letter sets from which the CM and VM stimuli were drawn were mutually exclusive. The set size and mapping variables were factorially combined to yield four experimental conditions: VM1 (varied mapping, set-size 1), VM4 (varied mapping, set-size 4), CM1 (consistent mapping, set-size 1), and CM4 (consistent mapping, set-size 4). Twenty-five percent of the trials in each block were drawn from each of these experimental conditions.

The letter stimuli measured approximately 8.0-mm high and 6.5-mm wide. Letters in the SS1 memory sets were presented in the center of the CRT, as were all probe stimuli. The SS4 memory sets were presented in 2 x 2 arrays centered on the middle of the CRT. The spacing between letters was approximately 8.0-mm horizontally and 5.0-mm vertically. To control for dominant-hand effects, assignments of dominant and nondominant hands to "Target" and "Nontarget" response keys were alternated from subject to the next. To control for condition-order effects, subblocks containing 30 VM1, VM4, CM1, and CM4 trials were presented randomly.

## PROCEDURE

Subjects were run in subgroups of three to six individuals and monitored continuously by project staff. Each subject was comfortably seated approximately 1 m from a desktop computer that presented stimuli and collected the subject's responses. A training session was held on each of the four mornings preceding the sustained-performance session. Practice totaled 7680 trials, equally distributed across the four experimental conditions (VM1, VM4, CM1, and CM4). The sustained-performance session was 13.5 h in duration. It began at 1930 hours in the evening of the last practice day and ended at 0900 the next morning. Subjects were asked to carry out a normal day's activities and to refrain from napping before reporting to the laboratory. The sustained-performance session consisted of nine "superblocks" of experimental tasks spaced 90 min apart. Each

superblock, in turn, comprised three experimental tasks.<sup>3</sup> The tasks performed during in each superblock were separated by breaks of approximately 5 min. Food and drink were available during a 20-min break at the end of each superblock.

At 0116 hours, seven randomly selected subjects received a capsule containing 10 mg/70 kg body weight of dextromethamphetamine hydrochloride in cornstarch filler. The remaining subjects received identical capsules that contained cornstarch alone. Standard double-blind procedures were followed. At the end of the session, subjects slept in the laboratory dormitory for at least 6 h, or as long as desired.

## DATA ANALYSIS

Reaction times were measured from stimulus onset to response onset. Responses associated with RTs of 100 ms or less were regarded as anticipation errors (fast guesses) and were examined in separate analyses. A lapse (nonresponse) was counted when a subject failed to respond to a stimulus. Lapse probabilities were estimated as proportions of stimuli that failed to elicit responses. Separate lapse-probability estimates were made for target and nontarget stimuli. Memory-trace strengths were expressed in units of the detection-theoretic sensitivity measure,  $d'$  (Green & Swets, 1966; Wickelgren & Norman, 1966). Values of  $d'$  were calculated by the formula:

$$d' = \Phi^{-1}[p(H)] - \Phi^{-1}[p(FA)] \quad (2)$$

in which  $\Phi^{-1}[p(x)]$  represents the inverse cumulative normal probability function evaluated at  $p(x)$ ,  $p(H)$  is the probability of a hit and  $p(FA)$  is the probability of a false alarm. The value of  $p(H)$  was estimated as the proportion of target-present trials on which the subject responded "Target present" after the fast-guess cutoff and before the onset of the next stimulus. The value of  $p(FA)$  was estimated as the proportion of all target-absent trials on which the subject responded "Target present" during an equivalent interval. Note that the procedure just outlined excludes nonresponse trials from the calculations of hit and false-alarm probabilities. Doing so avoids the occasionally voiced complaint that including lapse trials in accuracy calculations artifactually deflates measured performance by confounding fatigue-related increases in lapse probabilities with reductions in accuracy.<sup>4</sup>

## SIGNIFICANCE TESTS

Tests of significance were performed in mixed-design analyses of variance (mixed ANOVAs). The calculations were performed using the program, BMDP 2V (Dixon, Brown, Engelman, Hill, & Jennrich, 1988).

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<sup>3</sup>The memory-search task comprised an experiment embedded within the overall study. The data from the study's other experimental protocols are described in Stanny, McCardie, and Neri (1993). They are entirely consistent with the data presented here.

<sup>4</sup>Other than in sleep-deprivation research,  $p(H)$  is usually defined as is the conditional probability of a "Signal present" response given the presence of a signal. Similarly,  $p(FA)$  is usually defined as the conditional probability of a "Signal present" response given the absence of a signal (e.g., Green & Swets, 1966). In the present definition, nonresponses are ignored. So,  $p(H)$  is the conditional probability of "Signal present" given that a subject, indeed, responds to a signal (a target stimulus) and  $p(FA)$  is the conditional probability of "Signal present" given that a subject, indeed, responds to a nonsignal (a distractor). The two methods of calculating hit and false-alarm probabilities can yield quite different results when applied to data that contain substantial numbers of lapses.

The ANOVAs were factorial designs in which set size, stimulus-response mapping, and time were within-subject factors. Stimulus type comprised an additional within-subject factor in the analyses of RT, nonresponses, and fast guesses. The set size factor had two levels corresponding to the SS1 and SS4 conditions. Mapping had two levels corresponding to the CM and VM conditions. Time had nine levels corresponding to the nine superblocks of trials. Stimulus type had two levels corresponding to targets and distractors. The drug treatment comprised a between-subjects factor. It had two levels, corresponding to the methamphetamine and placebo conditions. Hypotheses concerning performance over time were tested in linear orthogonal-polynomial trend analyses of from the measures obtained in the nine blocks of trials.<sup>5</sup> The significance levels of  $F$  ratios with two or more numerator degrees of freedom were corrected for nonsphericity effects by the procedure of Huynh and Feldt (1976).

## RESULTS AND DISCUSSION

### TRACE STRENGTHS

Figure 1 shows trace strengths versus time in the four mapping and set-size conditions. Overall strength decreased from an initial value of  $d' = 3.34$  at 1953 to a minimum value near 2.63 (the mean value of  $d'$  in the 0453 and 0623 trial blocks). Trace strength then increased slightly to a final value of 2.78 at 0753, which probably was about an hour after the subjects' circadian minima. The linear component of the declining trend in strength, averaged across both groups of subjects, yielded an  $F(1, 11) = 12.83$ ,  $p = .0043$ .

Unsurprisingly, the strengths of long-term memories exceeded those of short-term memories, averaging 3.00 in the consistent mapping conditions as opposed to 2.72 in the varied mapping conditions,  $F(1,1) = 7.21$ ,  $p = .0212$ . Mean trace strengths were lower in the higher memory-load conditions, averaging 2.66 in the SS4 conditions versus 3.06 in the SS1 conditions,  $F(1, 11) = 56.35$ ,  $p < .00005$ . However, the difference between these means was largely due to the effect of memory load on short-term trace strengths: Long-term strengths were only slightly affected by load, averaging 3.01 in the CM1 condition versus 2.91 in the CM4 condition. In contrast, short-term strengths varied more strongly with load, averaging 3.02 in VM1 and 2.42 in VM4. The high sensitivities of short-term memories to load effects yielded a highly significant mapping-by-set-size interaction,  $F(1, 11) = 27.58$ ,  $p = .0003$ .

The strengths of long-term traces declined significantly during the night: The linear component of the decreasing trend in long-term (CM) strengths yielded an  $F(1, 11) = 12.73$ ,  $p = .0044$ . The strengths of short-term traces declined more rapidly than those of long-term traces, as evidenced by a significant contrast between the linear components of the long-term (CM) and short-term (VM) strength trends,  $F(1, 11) = 5.31$ ,  $p = .0417$ . Figure 2 shows the average strengths of CM and VM traces over time in the placebo and methamphetamine groups. The values in Fig. 2 have been averaged across the two memory loads because the difference between the CM and VM strength trends did not vary significantly with load. The data from the two groups are plotted separately because strengths increased sharply between 0153 and 0323 in the methamphetamine group ( $0+37$  to  $2+07$  postadministration). This was done simply for clarity; differences between the *trends* in VM and CM strengths were not significantly affected by methamphetamine (i.e., methamphetamine did not reduce the decline in  $d'$  per unit time more in VM conditions than in CM conditions).

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<sup>5</sup>With a few exceptions, discussed in the Results and Discussion, significance tests were limited to first-order polynomial trend components. This was done to avoid capitalizing on chance differences in the higher-order trend components.

The more rapid decline of short-term (VM) strengths than long-term (CM) strengths during the night is most clearly visible in the placebo group (Fig. 2). The data from the methamphetamine group are more difficult to interpret, due to the marked increase in strength shortly after methamphetamine administration and, in particular, the excellent short-term VM performance of the methamphetamine group at 0323--approximately the time at which methamphetamine plasma levels should have peaked (Cook et al., 1992; Shappell, Kearns, DeJohn, & Neri, 1993). Except during the period between 0153 and 0323, short-term strengths appear to have declined more rapidly than long-term strengths throughout the session.

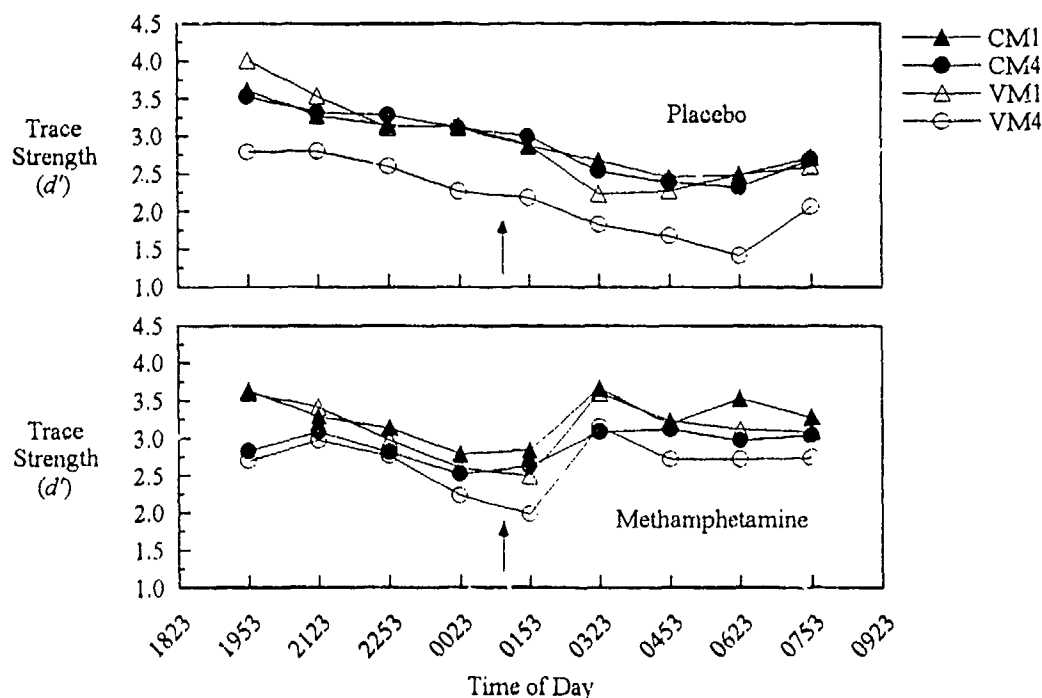


Figure 1. Trace strength versus clock time. CM = consistent mapping. VM = varied mapping. The numbers that follow CM and VM indicate set sizes. The arrows indicate drug administration time.

The overall decline in trace strength during the night was much larger in the placebo group than in the methamphetamine group,  $F(1, 11) = 13.80$ ,  $p = .0034$ . The large increase in strength during the 2 h immediately following methamphetamine administration appears to have counteracted an initial decline. The reality of this effect is suggested by the presence of a significant difference between third-order polynomial components of the groups' strength trends,  $F(1, 11) = 11.74$ ,  $p = .0057$ . This component appears to reflect variance attributable to the pair of bends in the methamphetamine group's strength-versus-time function at 0153 and 0323, respectively.

The effects of methamphetamine did not vary significantly with mapping condition or set size. The absence of an influence of methamphetamine on the difference between VM and CM performance may be contrary to intuition, as it seems reasonable to suppose that the stimulant would have enhanced attentional control processes, such as rehearsal. Such effects might be expected to improve attentionally dependent (VM)

performance more than automatic (CM) performance. A close inspection of the methamphetamine group's mean trace strengths during the blocks following drug administration indicates that VM strengths did, on average, increase more than CM mean strengths until 0323, approximately the time at which plasma methamphetamine levels should have reached their maxima (Cook et al., 1992; Shappell et al., 1993). This nonsignificant trend, however, disappeared by 0453.

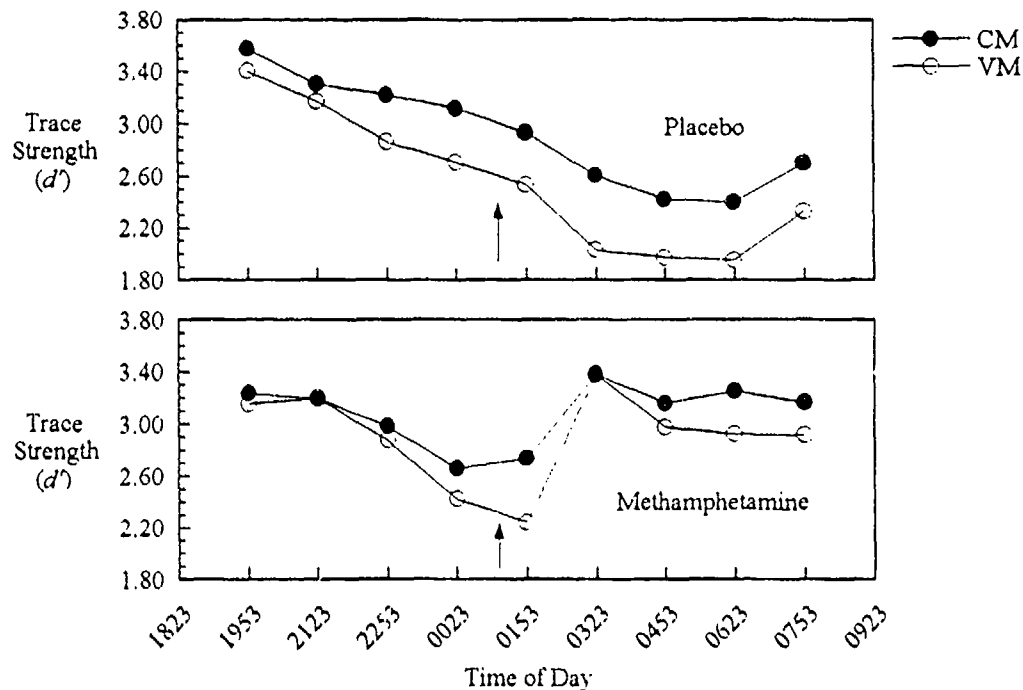
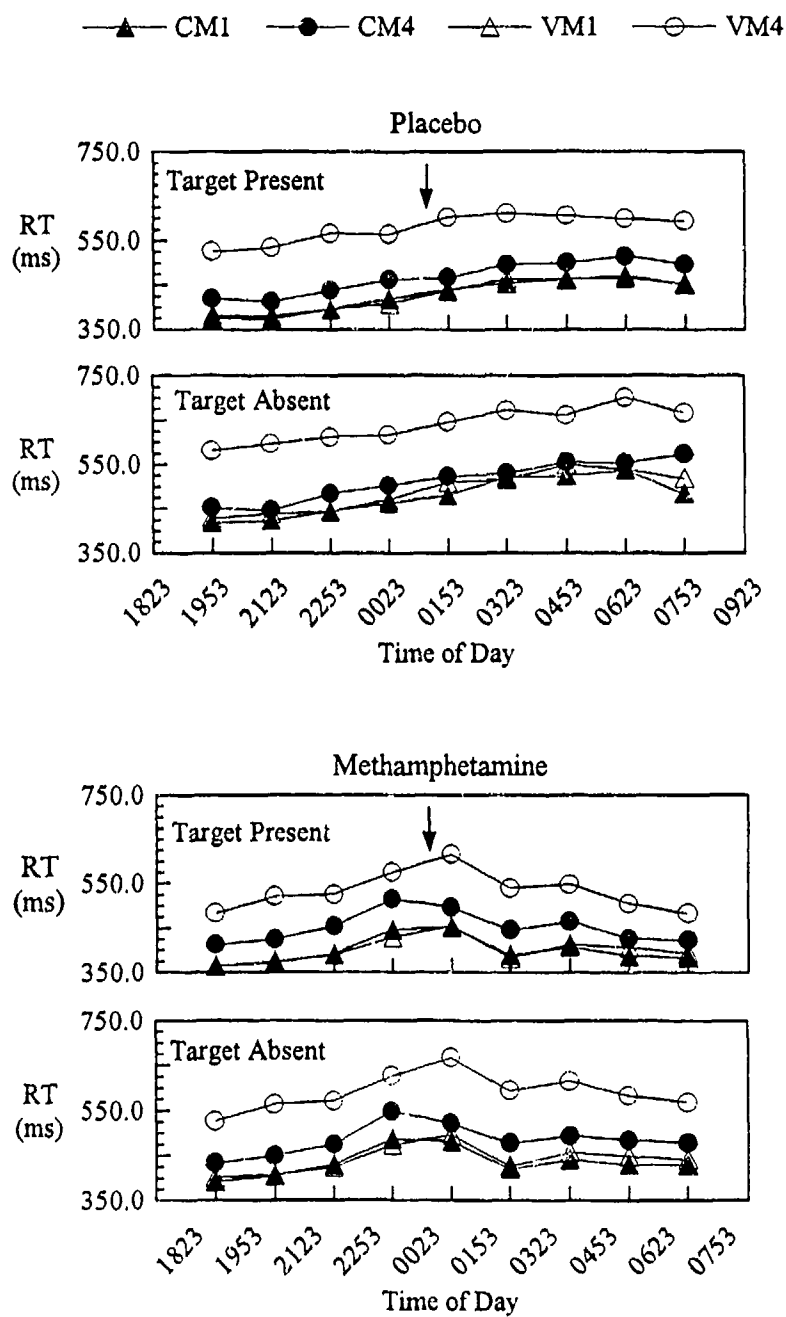


Figure 2. Mean CM and VM trace strengths over time. The values shown here are averaged over memory-set sizes. CM = consistent mapping. VM = varied mapping. The arrows indicate drug administration time.

## REACTION TIMES

Overall correct-response reaction times (averaged across groups, memory loads, and mapping conditions) increased from 434.98 ms at 1953 hours to a maximum of 518.09 ms at 0153 and then decreased to a final 489.67 ms at 0753. The linear component of the (increasing) trend in RT over time yielded a highly significant  $F(1, 11) = 30.27$ ,  $p = .0002$ . Correct-response RTs, averaged across memory loads, were 55.92-ms longer in VM conditions than in CM conditions (512.75 ms vs. 456.83 ms,  $F(1, 11) = 135.28$ ,  $p < .00005$ ). Correct-response RTs averaged 48.56-ms shorter on target-present trials than on target-absent trials,  $F(1, 11) = 99.30$ ,  $p < .00005$ , a standard result in matching designs, of which memory search is an example (Luce, 1986).

That subjects achieved of a degree of automaticity in the consistently mapped experimental conditions was suggested by the much smaller increases in RT with memory load in CM conditions than in VM conditions,



**Figure 3.** Mean correct-response reaction times (RTs) on target-present and target-absent trials. The curves are labeled as in Fig. 1. The arrows indicate drug administration time.



$F(1, 11) = 137.818, p < .00005$  (see Fig. 3). The mean RTs of correct "Target present" responses in CM conditions increased by 46.36 ms as set size increased from 1 to 4 items. In contrast, the RTs of correct "Target present" responses in VM conditions increased by 141.61 ms as set size increased from 1 to 4 items. Thus, decision speeds were less sensitive to memory load when stimulus-response mappings were consistent and (through practice) committed to long-term memory than when stimulus-response mappings varied randomly and (of necessity) were held in short-term memory.

According to Sternberg's (1966, 1969) serial search model, the RTs for correct "Target present" responses in CM conditions imply that, on average, subjects required only 15.45 ms/item to retrieve an item from *long-term* memory and compare it to a probe stimulus. Correct "Target absent" decisions yielded approximately the same result, 14.17 ms/item. In contrast, the results for correct "Target present" responses in attentionally controlled (VM) search conditions imply that, on average, subjects required 47.20 ms/item to retrieve an item from *short-term* memory and compare it to a probe. In this case also, correct "Target absent" decisions yielded about the same result, 49.52 ms/item.

Placebo-group correct-response RTs increased from an overall mean of 447.92 ms at 1953 hours to 547.64 ms at 0623 hours (a change of 99.72 ms), and then decreased, slightly, to 529.61 ms at 0753 (see Fig. 3). Methamphetamine-group RTs increased very rapidly *prior* to drug administration, from 422.05 ms at 1953 to 523.03 ms at 0153 (a difference of 100.98 ms). However, by 0323 hours (2+07 postadministration), RTs in the methamphetamine group decreased to 459.74 ms. Thereafter, RTs in the methamphetamine group averaged 462.89 ms (from 0453 to 0753), about 41-ms longer than at the beginning of the session. The (linear) trends in the placebo and methamphetamine groups' RTs differed significantly,  $F(1, 11) = 13.33, p = .0038$ , suggesting that methamphetamine, in fact, reduced the overall trend toward increasing RTs.

An inspection of the kink in the methamphetamine-group RT data shown in Fig. 3 suggests that the stimulant may have *reversed* an initial increase in methamphetamine-group RTs that began during the early trial blocks. An effect of this type would seem consistent with the apparent reversal of an initial decline in trace strength mentioned previously (recall the significant contrast between the groups' cubic trends in  $d'$ ). A contrast of the cubic components of the drug and placebo groups' RT trends, performed to check this idea, yielded a reasonably strong trend toward significance,  $F(1, 11) = 3.93, p = .0728$ .

## LAPSES

Lapse (nonresponse) probabilities increased systematically during the night, beginning at an overall average of 0.001 at 1953, peaking at 0.131 at 0623, and decreasing to a final value of 0.074 at 0753 (see Fig. 4). The linear component of the trend in lapse probabilities (averaged across stimuli and drug, mapping, and set-size conditions) yielded an omnibus  $F(1, 11) = 11.90, p = .0054$ . As Fig. 4 illustrates, the increase in lapse probability was much larger in the placebo group than in the methamphetamine group. Lapses in the placebo group increased from an overall probability of 0.001 at 1953 hours to a maximum of 0.246 in the next-to-last block of trials, at 0623.

In striking contrast, lapse probabilities in the methamphetamine group increased from an average of 0.002 at 1953 hours to a maximum of 0.124 at 0153 (which was just 37 min postadministration). Thereafter, lapses were almost completely suppressed in the methamphetamine group, averaging 0.036 at 0323 and remaining below 0.020 during the three final blocks of trials. The difference between placebo- and drug-group lapse trends over time yielded a significant  $F(1, 11) = 10.66, p = .0075$ .

An examination of the shapes of the methamphetamine group's lapse trends shown in Fig. 4 suggests that the stimulant may have reversed an increase in lapse probabilities that began during the early trial blocks. A test of this hypothesis (a between-groups contrast of cubic trends in lapses) produced an  $F(1, 11) = 11.28$ ,

$p = .0064$ . The apparent reversal of an increasing trend in lapses strongly resembles the apparent reversals of trends in strength and RT discussed previously.

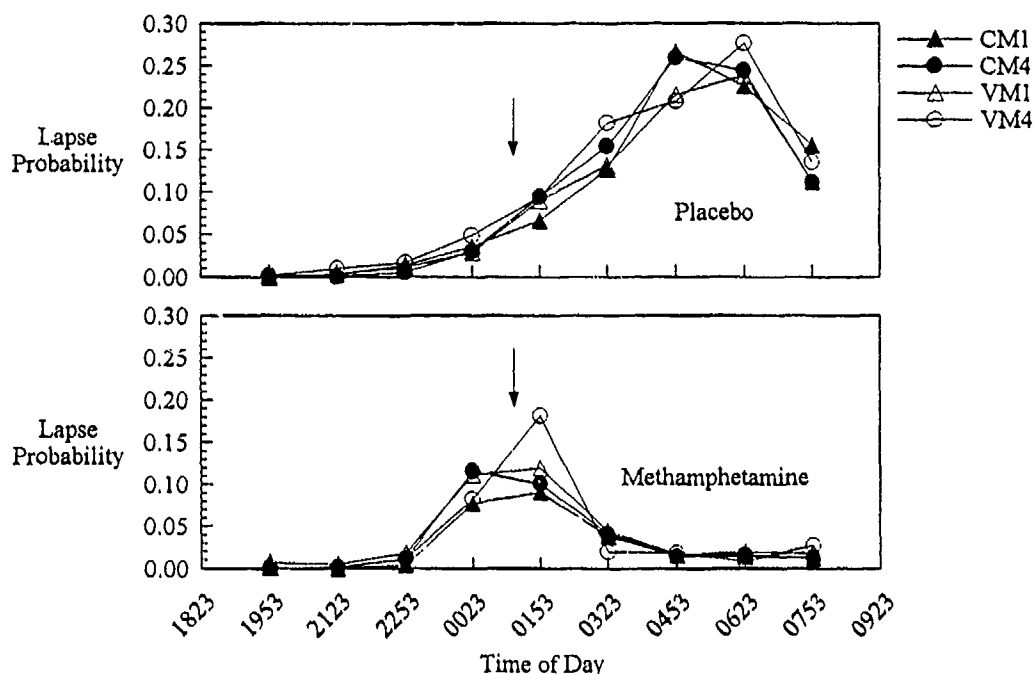


Figure 4. Lapse probability versus time. The curves are labeled as in Figure 1. The arrows indicate drug administration time.

Neither the memory load variable nor the mapping variable significantly affected lapse probabilities. With the exception of what might be a wild point in the methamphetamine group's VM4 data at 0153 hours, the nonresponse probabilities in all four mapping and set-size conditions cluster fairly tightly (see Fig. 4). Hence, the data provide little evidence to suggest that either memory load or degree of automaticity had any influence on the probability of a lapse.

## FAST GUESSES

Fast guesses (responses with RTs  $\leq 100$  ms) increased from an overall average of 0.06/block at 1953 hours to a mean of 5.04/block at 0453 and then declined slightly during the remainder of the session. The linear component of the increasing trend in fast guesses was significant,  $F(1, 11) = 5.13$ ,  $p = .0477$ . An examination of Fig. 5 suggests that fast guesses increased more rapidly in the methamphetamine group than in the placebo group until 0153 (37 min postadministration) and then decreased somewhat; whereas fast guesses continued to increase until 0453 in the placebo group and decreased only slightly thereafter. Although an inspection of Fig. 5 suggests that the methamphetamine treatment might have slightly reduced fast guesses, the groups' linear trends failed to differ significantly,  $F(1, 11) = 1.43$ ,  $p = .2568$ . Higher-order trend components also failed to differ. It might be noted that an average count of 4.47 fast guesses in a block of 360 trials (the maximum reached by the methamphetamine group) corresponds to only 1.2% fast guesses, and an average of 6.9.0 per block (the maximum of the placebo group) corresponds to only 1.9% fast guesses. Inasmuch as

subjects had been asked to respond as quickly as possible consistent with moderate error rates, and were not penalized for fast guesses, individuals in both drug groups appear to have maintained reasonably conservative response criteria throughout the experiment.

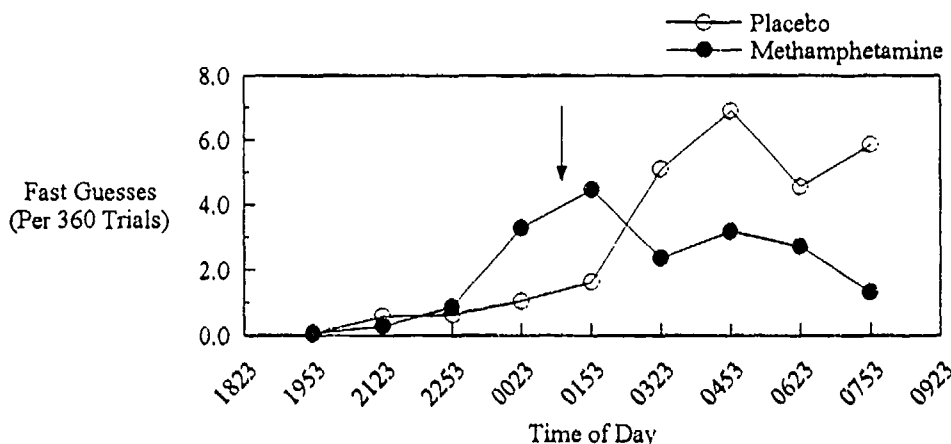


Figure 5. Mean anticipation (fast-guess) counts versus time. The values shown here have been averaged over the mapping and set-size conditions. The arrow indicates drug administration.

## SUMMARY

The 10 mg/70 kg methamphetamine treatment yielded marked reductions in the effects of sustained performance on short- and long-term recognition. Memory-trace strengths and RTs were uniformly less affected in the methamphetamine treatment group than in the placebo group. Indeed, trace strengths returned to nearly their initial values within 2+07 postadministration. Lapses were largely suppressed in the methamphetamine treatment group. Although methamphetamine yielded faster responses, methamphetamine also yielded more accurate responding (higher values of  $d'$ ). This combination of effects is consistent with the hypothesis that methamphetamine produced genuine increases in memory efficiency. They are inconsistent with the hypothesis that the drug merely caused subjects to trade accuracy for speed. The absence of any tendency for methamphetamine to increase fast guesses, despite the fact that methamphetamine increased response speeds in general, lends further support to this conclusion. These results do not, of course, logically eliminate the possibility that methamphetamine caused some degree of speed-accuracy trading. They indicate, however, that the methamphetamine treatment yielded increases in performance that were more than sufficient to compensate for any speed-accuracy tradeoffs that occurred.

The strengths of short-term memories were affected more by sustained performance than those of long-term memories. The evidence was the more rapid decline of  $d'$  in VM conditions than in CM conditions. (The long-term memories were associations between specific stimuli and specific responses established in CM training.) Nevertheless, the strengths of long-term memories also declined during the session. These results are partially consistent with the sleep-deprivation results of Williams et al. (1959, 1966), who observed large effects of sleep deprivation on short-term memories but only small and nonsignificant, effects on long-term memories acquired before sleep deprivation. The discrepancy may be a matter of degree. Sustained-performance designs,

like the one used here may produce larger performance deficits than sleep-deprivation designs of the type used by Williams et al. (Mullaney, Kripke, Fleck, & Johnson, 1983). Conceivably, the performance demands of our study potentiated effects on long-term memory that were too small to measure in the experiments of Williams et al. (1959, 1966).

The major procedural difference between VM and CM conditions in our study was that, in VM conditions, subjects were required to form a new set of stimulus-response associations at the beginning of each set of 30 trials. In the CM conditions, these associations were established before the experimental session and did not change during the experiment. Hence, the more rapid decline of VM (short-term) memory-trace strengths may be attributable to an influence of sustained performance on the formation of new associations. This conclusion is consistent with the contention of Williams et al. (1966) that sleep deprivation impairs trace formation. The possibility that lapses contributed to the difficulty subjects had forming new traces was not ruled out in the present study. Williams et al. (1966) assumed that having subjects write down stimuli as they heard them effectively ruled out such effects. However, as Polzella (1975) has noted, this assumption is questionable because having subjects write down stimuli would not eliminate the effects of lapses on rehearsal processes. Because memory performance varies directly with rehearsal (Rundus & Atkinson, 1970), an effect of lapses on rehearsal would be expected to impair acquisition and retention. Patrick and Gilbert (1898) observed what may be a related phenomenon, noting that effects of repeated lapses eventually caused one of their subjects to give up attempting to commit a list of figures to memory. "A kind of lapse would constantly undo all work done" (p. 479). In our experiment, it seems probable that lapses that occurred while subjects studied memory sets affected the strengths of short-term memories more than those of long-term memories: Lapses during the presentation of memory sets would be expected to reduce the strengths of new, short-term associations by impairing their acquisition. Such lapses would not be expected to retroactively influence the acquisition of long-term associations developed over thousands of CM trials preceding the main experimental session. Consistent with this idea, several subjects observed that forgetting the current memory set had little effect in CM conditions because they knew how to respond as soon as they saw the next target.

The absence of an effect of fatigue on the slopes of RT-versus-set-size functions suggests that fatigue might not have affected the retrieval process. This conclusion would be more compelling if the strengths of long-term memories had not declined during the experiment. Williams et al. (1959, 1966) concluded that retrieval may be unaffected by sleep loss after failing to observe effects of sleep deprivation on the recall of previously acquired memories. A decline in the strengths of previously acquired memories in our experiment seems inconsistent with their results. However, our subjects experienced circadian and work-repetition effects that were not present in the sleep-deprivation studies of Williams et al. Conceivably, the phenomena we observed were due to repetitive-work or circadian effects that sleep deprivation alone does not produce. As mentioned previously, it also is possible that the additional stressors in our experiment may have potentiated a generalized effect of fatigue on long-term memory that was too small to detect in previous studies. Finally, our performance measure was recognition, whereas those of Williams et al. were recall. Logically, recognition and recall differ at least in those operations that convert the output of the memory system into task performance (Tulving, 1982). In our experiment, occasional failures to encode probe stimuli, perhaps caused by brief lapses, could have produced recognition errors that reduced the (measured) strengths of long-term memories. Comparable reductions in trace strength might not have been observed if subjects had been allowed to simply recall items with little time pressure. We suspect resolution of these issues may require further research.

The results of the present study are consistent with suggestions that automatized performance is more resistant to stress effects than attentionally controlled performance (Fisk & Scerbo, 1987; Fisk & Schneider, 1981, 1982; Hancock, 1986). Automatic memory search was uniformly better than attentionally controlled search. Trace strengths in CM conditions were higher than in VM conditions at the beginning of the experiment and tended to remain so throughout the night. Consistent with the results of Maylor and Rabbitt (1988), however, practicing the task until it could be performed with some automaticity did not prevent the occurrence of substantial stressor-related performance deficits: Large reductions in  $d'$  occurred in automatic- and

controlled-search conditions alike (Fig. 1). In particular, lapse probabilities were nearly equal in VM and CM conditions (Fig. 4). This result suggests that training the task to automaticity offered little protection from what is arguably the most profound and dangerous phenomenon of sleep deprivation.

## CONCLUSIONS

1. The 10 mg/70 kg methamphetamine treatment largely counteracted recognition memory deficits that occurred in 12 h of sustained performance during a night of sleep deprivation. The treatment substantially reduced the effects of sustained performance on both accuracy and speed of recognition.
2. Nonresponses (lapses) were prevalent during the early morning hours. Lapses equally affected long- and short-term memories. Lapses equally affected highly practiced, automatic recognition and nonautomatic recognition. The methamphetamine treatment almost completely suppressed lapses.
3. The methamphetamine treatment did not lead to risky, impulsive responding. This was evidenced by a genuine increase in accuracy after methamphetamine was administered and by the absence of any effect of methamphetamine on impulsive responses (fast guesses).
4. The methamphetamine treatment became effective about 2 h postadministration. Its effects did not diminish greatly through the final round of testing, about 7 h postadministration.
5. Sustained performance impaired short-term memories more than it impaired long-term memories. The methamphetamine treatment counteracted these effects by increasing the strengths of both short- and long-term memories. The effects of methamphetamine on short- and long-term memories were not significantly different.
6. Highly practiced, relatively automatic performance was somewhat less influenced by fatigue than nonautomatic performance. Nevertheless, automatic performance was substantially degraded by fatigue.

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- Stanny, R. R., McCardie, A. H., & Neri, D. F. (1993). *Effects of methamphetamine on vigilance and tracking during extended wakefulness* (Report No. 1386). Pensacola, FL: Naval Aerospace Medical Research Laboratory.

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Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302 and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503				
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE November 1993	3. REPORT TYPE AND DATES COVERED Interim 1993		
4. TITLE AND SUBTITLE Effects of Methamphetamine and Fatigue on long- and Short-term Memory		5. FUNDING NUMBERS 63706N M0096.002-7010 DN248502		
6. AUTHOR(S)  R.R. Stanny, A.H. McCardie, and D.F. Neri				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)  NAVAEROMEDRSCHLAB 51 Hovey Road Pensacola, FL 32508-1046		8. PERFORMING ORGANIZATION REPORT NUMBER  NAMRL-1387		
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Naval Medical Research and Development Command National Naval Medical Center 8901 Wisconsin Avenue Bethesda, MD 20889-5606		10. SPONSORING / MONITORING AGENCY REPORT NUMBER		
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION / AVAILABILITY STATEMENT  Approved for public release; distribution unlimited.		12b. DISTRIBUTION CODE		
13. ABSTRACT (Maximum 200 words) We examined the effects of a 10 mg/70 kg oral dose of <i>d</i> -methamphetamine HCl on fatigue-related deficits of short- and long-term memory. We used a recognition memory-search task with two memory loads. In one experimental condition, stimuli were committed to long-term memory (LTM) and performance was rendered automatic by extensive practice with consistently mapped stimuli and responses. In a second condition, the task was organized so that recognition depended on short-term memory (STM) despite equally extensive practice. After 7680 training trials, 13 subjects performed the task at 90-min intervals in a 13.5-h, sustained-performance session that began at 1930 and ended at 0900. At 0116, seven subjects were administered capsules containing 10 mg / 70-kg body weight <i>d</i> -methamphetamine HCl, double-blind. The remaining subjects were administered a placebo. Memory-trace strengths and decision speeds declined during the early part of the night in all experimental conditions. The methamphetamine treatment reversed these effects within approximately 2 h of administration. The methamphetamine treatment also reversed an increasing trend in lapse probabilities. The stimulant did <i>not</i> merely produce criterion shifts that led subjects to respond impulsively (more rapidly but less accurately). These results suggest that the methamphetamine treatment produced genuine increases in accuracy of recognition and that any criterion shifts that may have occurred were more than compensated for by increased accuracy.				
14. SUBJECT TERMS Human Performance, Sustained Operations, SUSOPS, Sustained Performance Continuous Operations, CONOPS, Continuous Performance, Stimulant Drugs, Methamphetamine, Amphetamine, Sleep deprivation, Sleepiness, Fatigue, Memory, Short-Term Memory, Long-Term Memory, Automaticity			15. NUMBER OF PAGES 22	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT  Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE  Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT  Unclassified	20. LIMITATION OF ABSTRACT  SAR	